DIFFUSION BOND INSPECTION USING A PULSED DIGITAL REFLECTION ACOUSTIC MICROSCOPE

Leonard J. Bond, Amit K. Som, and Klara Shiloh

NDE Centre, Mechanical Engineering Department
University College London, Torrington Place
London, WC1E 7JE, United Kingdom

Kevin J. Taylor

British Aerospace plc
Warton Aerodrome, Preston, PR4 1AX, United Kingdom

INTRODUCTION

In the joining of metals there is a growing use of the family of advanced methods for solid state bonding, which includes friction welding and diffusion bonding. With these joining techniques a new range of quality and inspection problems are encountered. These problems, in particular for diffusion bonds, have become well known and there are the requirements for inspection techniques which can be used to give data to correlate with the bond's mechanical strength. Various studies [1,2,3] have considered the destructive examination of bonds and categorised these in terms of characteristics seen in an examination of micrographic sections. A range of ultrasonic studies have also been undertaken [4,5,6], however conventional C-scan techniques have yet to be shown to provide the required reliable bond characterisation.

This paper reports a preliminary investigation using a Pulsed Digital Reflection Acoustic Microscope (PDRAM) (25-100 MHz) to characterise the diffusion bond lines between sheets of titanium.

PULSED DIGITAL REFLECTION ACOUSTIC MICROSCOPE (PDRAM)

A pulsed digital reflection acoustic microscope (PDRAM) has been developed at UCL for the characterisation of advanced engineering materials including ceramics, composites, powder metals and also advanced bonding processes such as diffusion bonding [7,8]. The instrument was designed around a commercial ultrasonic unit, scanning frame and an IBM PC/AT microcomputer which acts as both the system controller and as a powerful signal processor for the system. The block diagram for the system is shown as Fig.1. The system functions in a pulse-echo configuration, and the frequency of operation depends on the transducer selection and instrumentation settings. Measurements are made using pulse excitation which gives a wide bandwidth ultrasonic pulse with a centre frequency in the range 25 MHz to 100 MHz with the transducer being the main component that sets the pulse centre and

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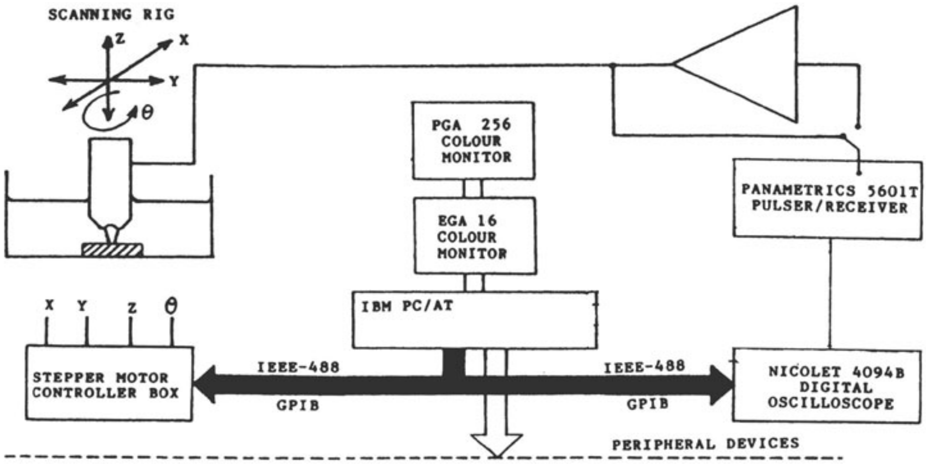

Fig 1. Block diagram for UCL Pulsed Digital reflection Acoustic Microscope (25-100 MHz).

bandwidth employed. The use of a pulsed system also enables spatial resolution between reflections to be achieved. All but one of the major elements selected for use in the system are commercially available modules. The exception is a custom designed gate board which has been developed for this project. The various modules have been integrated into the system at UCL with specially written control software. For the digital data capture the A/D conversion rate is up to 500 MHz (2 nsec sampling).

IMAGING TECHNIQUES

The system has been designed so that it is flexible and at any point the full digitised "RF" wave-form is available or the signal can be fed into a gated peak detector. The various data can then be displayed in a range of modes. The first mode is as a conventional A-scan or "RF" data display for a single set of data giving time/ amplitude data. The second mode is the B-scan or "waterfall plot" which is s stack of 'RF' traces along a selected scan line. The third mode is as a conventional acoustic microscope or C-scan system to give either a surface image obtained with compression waves focused in a plane and using the peak detector. The fourth mode involves the use of 'leaky Rayleigh' waves for surface imaging and in this mode a wide aperture transducer is employed which is defocused, by moving it closer to the sample, to such an extent that the generation of leaky Rayleigh waves takes place on the sample surface. Various forms of image are then possible by applying the system gate to the Rayleigh wave components. In addition, line scan data in the form of V(x) and V(z) curves are also available. For all data collected averaging can be applied at each data point to improve the signal to noise ratio. In most cases between 10 and 100 time sequences were averaged to give data for each scan point or pixel. These various forms of data output are described in more detail elsewhere [7,8].

CONVENTIONAL C-SCAN INSPECTION OF DIFFUSION BONDS

Various groups have reported the use of high frequency ultrasonic C-scan systems to inspect a range of diffusion bonds [4,5,6,7,8]. In such inspections it has been shown that major voids and inclusions can be detected, with limits set by the instrument used, material attenuation and transducer frequency resolution limits. Using the PDRAM, various C-scan images of features in diffusion bond line zones were obtained. In the measurements made at UCL on diffusion bonds between sheets of titanium in each scan of an area about 10 mm by 10mm on average 2 or 3 significant voids or inclusions were seen with dimensions above 50 µm. These inspections were found to give identical results irrespective of bond condition determined from optical examination of micrographic samples obtained from destructive examination of the plate.

Ultrasonic Inspection Capability

It is found that with the UCL PDRAM operating at a centre frequency of 50 MHz that isolated defects with planar dimensions well below 100 µm can be detected and imaged [8]. It is not however the population of small (about 200 µm diameter) isolated flaws that are usually found to limit the mechanical strength of the diffusion bond; it is properties of the diffusion bond line between the discrete 'macro-flaws', (voids or inclusions) above 50 µm. It has however yet to be shown that ultrasonic C-scans are capable of giving adequate discrimination between acceptable and unacceptable bonds, determined from optical examination of micrographic samples or from destructive shear strength examinations.

It was therefore felt to be necessary to seek a greater understanding of the acoustic response of a diffusion bond line, including the number, size and distribution of micro-flaws and thin voids with dimensions of the order of 10 µm if inspection parameters are to be optimised. It is also necessary to seek a definitive answer to the question as to whether ultrasonic inspection is a suitable tool to provide a non-destructive measurement which can be related to diffusion bond-line strength.

LEAKY RAYLEIGH WAVE INSPECTION OF DIFFUSION BONDS

Leaky Rayleigh waves in an acoustic microscope used for surface imaging would appear to provide the desired ultrasonic bond-line characterisation tool [9,10,11]. Leaky Rayleigh waves are generated when a wide aperture transducer is defocused and compression waves are incident at the Rayleigh critical angle.

For the measurement of near-surface properties to a depth of about 1.5 wavelengths, (about 150 µm at 50 MHz) Rayleigh wave surface imaging can be used directly as an inspection tool. For cases where the bond line is at greater depths the Rayleigh wave imaging can still serve as a useful tool to study the characteristics of acceptable and unacceptable bonds, in samples prepared for edge-on optical examination. Such samples are prepared as a routine part of the diffusion bonding quality control development process. The use of Rayleigh waves for imaging purposes is not in its self novel and it has been reported elsewhere (e.g. [10,11]). The basic geometry for the generation of leaky Rayleigh waves with a defocused transducer is shown as Fig 2.

This condition is met whenever a wide aperture transducer is defocused and rays that exceed the critical angle for the fluid solid combination are present. When the received signal for the system shown as Fig.2. is considered it is found that for a flat sample the directly reflected compression wave and the leaky waves are coincident at the focal point, and that they increasingly separate as the system is defocused [10]. The variation with defocus in a CW or tone burst instrument can also be used for the generation of the so called V(Z) curve and material characterisation [12].

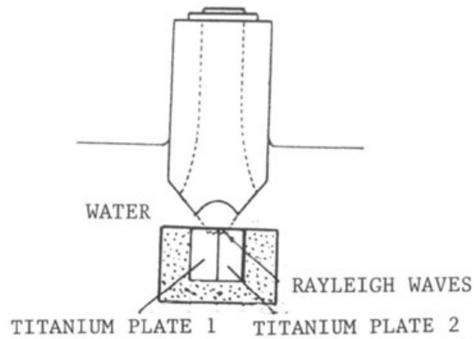

Fig 2. leaky Rayleigh wave inspection configuration.

Diffusion Bond Line Imaging

As a part of the normal quality control process, samples of diffusion bonded titanium-titanium plate are prepared as micrographic samples, used for optical examination, as a part of the process development and verification procedure. These provide the bond-line in section, normal to the free surface, and on the basis of features seen in the optical examination these are classified as 'acceptable' or as 'unacceptable'. Such samples are also suitable for leaky Rayleigh wave inspection which can be used to determine the acoustic properties of both plate and bond-line material.

Samples of diffusion bonded titanium were examined and examples of these are shown in Fig 3a and 3b. When the sets of images were compared with the corresponding optical micrographic examinations classification it was found that Fig 3a corresponded to an 'acceptable' bond and Fig 3b corresponded with an 'unacceptable' bond.

In addition to C-scan images V(x) curves or lines scans were produced using data given in the images in individual lines of pixels taken across the bond lines and this data for the two cases shown in Fig 3 are given as Fig 4.

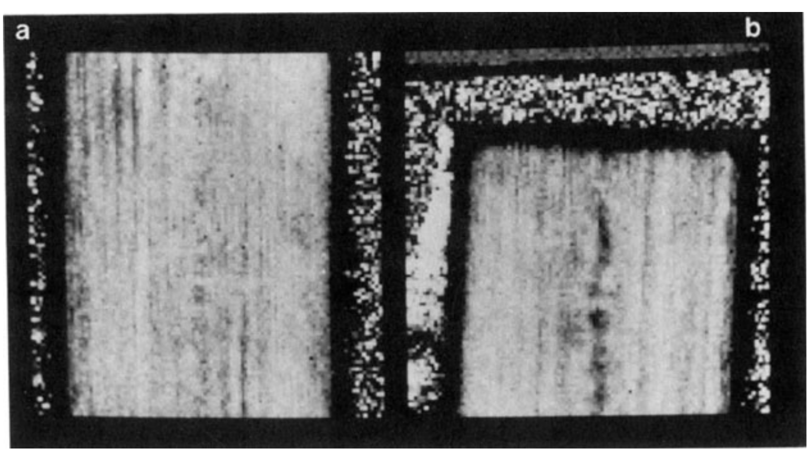

Fig 3. Leaky Rayleigh wave images of acceptable and unacceptable bonds.
a. acceptable bond. b. unacceptable bond.

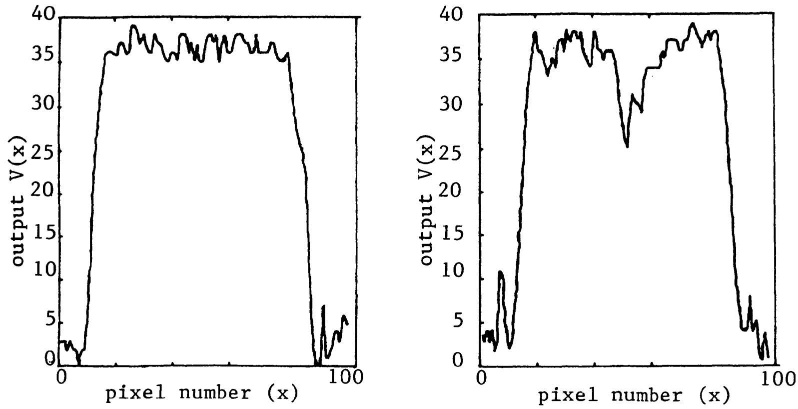

Fig 4. Line scans or V(x) signatures across (i) acceptable and (ii) unacceptable bond-lines.

It is seen in Fig 4 that for an unacceptable bond condition there is a clearly measured change in signal level. In both these cases the same number of averages were applied and all other experimental conditions were kept the same. If the dip in the V(x) curve is measured as (-N dB) it has been found that the magnitude of 'N' is larger for unacceptable bonds and the value of 'N' would appear to be proportional to the bond line reflection coefficient. For the case of Rayleigh wave interaction with a slit a theoretical analysis has been provided by Somekh et al [13]. The relationship between the 'N' value and reflection and transmission characteristics and their correlation with the optical classification, as well as the theory for V(x) curves, is currently being investigated and an extension sought to give an analysis for diffusion bond line interaction.

A possible ultrasonic method for the calibration of these bonding conditions would therefore appeared to have been found. Given that it was now shown to be possible to image diffusion bond line zones and identify acceptable and unacceptable samples of diffusion bond line it was then necessary to seek to relate the leaky Rayleigh wave image data to the conventional C-scan response.

DIFFUSION BOND-LINE CHARACTERISATION

The diffusion bond-line, when it is unacceptable, is a weak scattering layer and for the samples considered in this study a 'sandwich model' was adopted to describe the layer. For real diffusion bond-lines between two media if there is no significant diffusion, they are in contact but not stuck. There is a step change of properties at the bond-line, which may include a thin intermediate layer. For a perfect bond there are no voids, inclusions or changes of properties and material is continuous and uniform. Such a perfect bond will have no reflection, scattering or variation in attenuation properties, when compared with the parent material. When real bond-lines are examined optically changes in grain size, cracks and small voids are all observed and these can be expected to produce some change in reflection coefficient. If any form of intermediate or activation layer is introduced in the process this can be expected to cause localised changes in material properties as it diffuses. The diffusion rates are predictable and if the initial condition is a 'sandwich' this will then spread exponentially, and reduces in height as the diffusion occurs.

In the measurements which produced Figs. 3 and 4 the properties of this layer caused the contrast in the measurements with a 360^0 entry circle transducer and the analysis of these properties for an acceptable and unacceptable bond remains a current task. The distinction between the two cases can involve variations in sound velocity, absorption, scattering, reflection and transmission coefficients. The angular dependence of velocity measurements can be expected to characterise bond-lines.

If the nature of the contrast seen in the leaky Rayleigh wave images is to be understood and related to C-scan imaging conditions it is necessary to model the acoustic interaction and response. An idealised model for Rayleigh wave and welded-quarter spaces can be taken from geophysics and related to that for plane wave interaction with two media in welded contact, which gives the universal reflection and transmission coefficient curves, with variation in acoustic impedance, and this, and extensions to it, can apply to the diffusion bond interface system. The diffusion bond calibration scheme is shown in schematic form in Fig 5.

If the bond-line response in leaky wave inspection can be used to determine a reflection coefficient or transmission coefficient it can then be related to the plane wave response from a diffusion bond-line in C-scan mode. It has been found [9] that for weak scattering both the Rayleigh wave interaction on welded quarter spaces and plane waves on parallel interfaces follow the same universal reflection and transmission coefficient curves with variation in impedance contrast. For the line

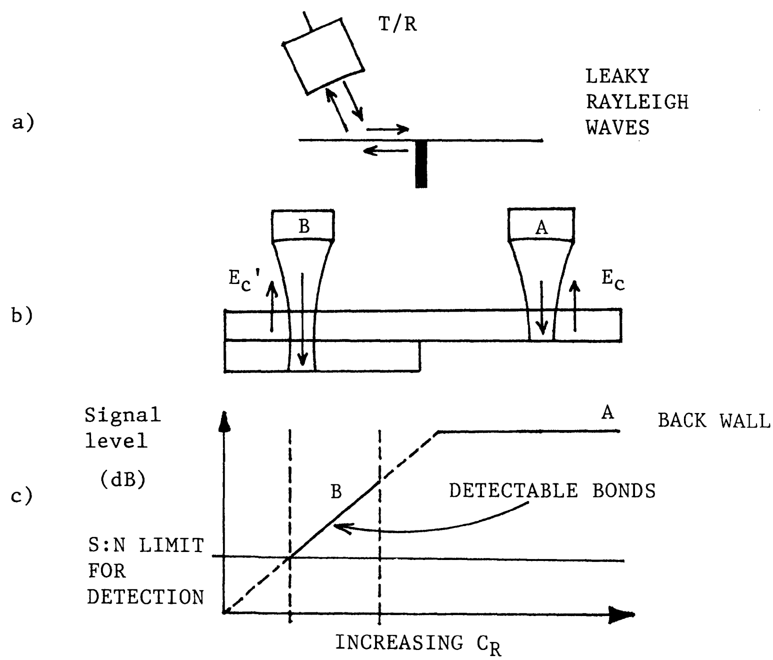

Fig 5. Diffusion Bond calibration scheme in schematic form.

a. Leaky Rayleigh wave interaction with welded quarter spaces to give Cr, reflection coefficient.
b. Plate calibration. Ec is the back wall echo. Ec', signal from diffusion bond.
c. System response estimation, giving S:N limits and relationship between signal level and Cr.

scan given in Fig 4 the noise level was seen to be at about 12 % (-18 dB) of the level of the measured transmission signal. The measured dip in the signal level is typically about 30% reduction (-3 dB) compared with the mean level of the signal in the bulk material. The background fluctuations in the V(x) curve across the plate material is typically found to be about ± 5 %, (± 0.5 dB), and this sets a detection limit, although the position of the bond-line is in general known.

For the system shown in Fig 5 the various acoustic responses can therefore be related, to a first approximation, by;

$$Ec' = Cr\,[\,Ec\,] \tag{1}$$

where Cr is the refection coefficient determined from leaky Rayleigh wave measurements.
Ec is the back wall echo response.
Ec' is the predicted bond line response.

When the back wall echo (Ec) signal level has been determined this also gives the system signal to noise limit for detection.
When there is no acoustic contrast at the bond-line, i.e, a perfect bond there will be no reflected signal. As the reflectivity of the bond-line increases a reflected signal will at some point come above the S:N limit. Alternatively the transmission coefficient and detection limit can be determined in a similar way to that shown above. In some situations the transmission is the directly measured property. The procedure outlined above should enable both the frequency dependent reflection coefficient for various diffusion bond lines to be determined and compared across a range of samples and materials and this work is now in progress.

The effect of plate material attenuation and variations in wavefield parameters can also be included in the calibration back wall echo or transmitted signal if measurements are not being made on the same thickness plate.

INSPECTION OPTIMISATION AND CALIBRATION

The best calibration route for the inspection methodology would appear to be;

i. take metalographic samples for conventional examination.
ii. perform leaky Rayleigh wave measures using PDRAM.
iii. determine expected degree of contrast for bond-line inspection.
iv. relate to the measurement window concept.
v. Estimate bond-line reflectivity/frequency response to determine if C-scan using either a. compression waves or b. shear waves can be expected to have the necessary sensitivity.

CONCLUSIONS

An ultrasonic inspection technique has been identified which would appear to have the potential to identify acceptable and unacceptable diffusion bonds for titanium at 50 MHz.

The leaky Rayleigh wave technique applied to micrographic samples would appear to have the potential to both optimise and calibrate the response of various types of diffusion bond samples and this data can then be related to conventional C-scan inspections.

It is shown how the difference between nominally 'acceptable' and 'unacceptable' diffusion bonded joints can be identified using the PDRAM system employed in a 'leaky Rayleigh' wave mode on samples that had been prepared for metalographic examination. Examples of images of sections through diffusion bonds in Titanium/Titanium made at 50 MHz have been shown. The difference between an acceptable bond and an unacceptable bond can be clearly seen. A model originally developed to understand Rayleigh wave interactions with faults in geophysics is presented applied to this problem.

It is then shown how both the model and the measured data can be related to the acceptability of a bondline. It is hoped that the Rayleigh wave data will then be shown to be related to bonding conditions when measurements are made at various frequencies in the more conventional 'C-scan' mode.

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